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ABSTRACT

Individual differences in cognitive structures resulting primarily from exposure to physics content were investigated in this research study. Thirty college students were divided into a treatment group of 19 and a control group of 11. A regression analysis indicated that individual differences were probably operative. An analysis of variance showed that 35 percent of the variance in cognitive structure correlation with content structure could be accounted for by group membership. Information was available on individuals' cognitive structure from subject weights obtained from INDSCAL. Tracing the development of individuals' cognitive structures and matching them to content presented is concluded to possibly increase students' comprehension and enthusiasm. (Author/LBH)

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Individual Differences among College Students in Cognitive Structure and Physics Performance

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* Based on Doctoral Dissertation completed at the Graduate Institute of Education, Washington University, St. Louis, Missouri

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Abstract

This research investigates individual differences in cognitive structures resulting primarily from exposure to physics content. Thirty college students, who were divided into a treatment group (N = 19) and a control group (N = 11), participated. A regression analysis indicated that individual differences were probably operative. An analysis of variance showed that 35% of the variance in cognitive structure correlation with content structure could be accounted for by group membership. Information was available on individuals' cognitive structure from subject weights obtained from INDSCAL. Tracing the development of individuals' cognitive structures and matching them to content presented may increase students' comprehension and enthusiasm.

Individual Differences among College Students in Cognitive Structure and Physics Performance

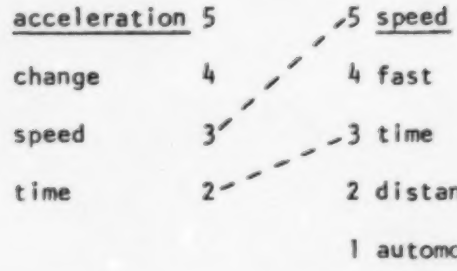
Few educators could deny that a goal of their educational endeavors is to maximize the potential with which each student is endowed. This individual optimization is consonant with the very principles on which our democratic nation is founded, where the strength of our government is invested in the intelligence and critical thinking of each of its voting members (Howes, 1970, p. 7). But individualization embodies a serious challenge to educators, who must somehow provide programs of studies and methods of instruction geared to the needs, interests, and capacities of individuals. It is obvious that estimates of the average performance of a group are of little use when planning instruction for the individual members of that group. Simple techniques are needed that will provide instructors with information about each individual's status. This paper focuses on cognitive structure development and presents a means of analyzing the progress of individual students' cognitive structure in approaching an established model of instructional physics content. The technique can provide the instructor with data which may indicate whether a student has differentiated concepts sufficiently to proceed or if additional instruction would be beneficial.

Evidence exists in recent literature which shows that researchers specifically involved in the field of science education have recognized

the need for tracing the cognitive development of science-relevant concepts. Shulman and Tamir (1973) and Novak (1971) expressed the need for data on concept growth over several years of coordinated science instruction. Shavelson (1971) suggested that future studies are needed to determine sources of individual differences in student achievement and to develop alternate means of representing content structure. He also recommends continuing attempts to relate cognitive structure to achievement. Books such as Howes' Individualizing instruction in science and mathematics (1970) testifies to the interest of educators in optimizing individual learning, for which knowledge of the characteristics of individual learners must be considered prerequisite.

Cognitive and content structures and their relationships have been investigated extensively prior to this research (Thro, 1976). Cognitive structure refers to the pattern of concepts established in long-term memory. In early works, frequency of responses played a prominent role in specifying cognitive structure (Noble, 1963; Deese, 1959, 1962; Johnson, 1964, 1965, 1967, 1969; Rothkopf & Thurner, 1970). However, Deese' introduction of a definition of associative meaning which claimed that two stimuli have the same meaning when they elicit responses in common enabled Johnson to use similarity judgments and Garskof and Houston's (1963) relatedness coefficients to establish relationships between lists of words. For example, if a person were to

produce the following lists of associations for acceleration and speed,



the relatedness coefficient for the two words would be

$$\frac{(3 \times 5) + (2 \times 3)}{(5 \times 5) + (4 \times 4) + (3 \times 3) + (2 \times 2) + (1 \times 1) - (5 - 4)^2} = .25.$$

These relatedness coefficients are functions both of the number of common words and of the order of appearance of the common words in the word association lists. The word associations are assumed to derive in whole or in part from the structures of the human mind.

Content structure is a definite relationship of concepts which are contained either in written or oral instructional material. In the domain of content, frequency of occurrence was again used to quantify the structure (Johnson, 1967, 1969; Rothkopf & Thurner, 1970). In the present study, a frequency tally of physics concepts in the energy chapter of Cromer's text (1974) was used as the basis for selecting the seventeen key concepts of the study. Frequency analysis underwent many refinements with the digraph techniques of Frase (1969), Shavelson (1971), and Geeslin(1973). Digraph analysis is rooted in the grammatical structure of sentences containing the key concepts chosen for a

study. The content structure of the energy selection in this study was determined by digraph analysis. However, it was not used as the model structure for the study because it did not span sufficient content for a developmental study which continued throughout a semester. Since the text is actually only a representation of the cognitive structure of its author (Shavelson & Stanton, 1975, p. 79), and because the teacher lectured from the text in the present study, it seemed reasonable to use the cognitive structure of the teacher, obtained from word association tests, to serve as the model of content structure.

This study hypothesized that the cognitive structures of individual college students will approach the instructional content structure at different rates. Word association tests taken by students provided the data for their cognitive structure, while the instructional content structure was derived from the instructor's word association tests. This hypothesis provided a framework for collecting the data provided by the subjects and instructor who each took five word association tests during the course of a semester.

Methodology

Subjects

Thirty (30) subjects served in this study. The 30 subjects were divided into a treatment group (N = 19) and a control group (N = 11). The treatment group was composed of 15 female and 4 male students who

comprised a General Physics Course at a private college. The 11 subjects in the control group were students not enrolled in a physics course who had little experience in the sciences and who were willing to participate in the study.

Instructional Material

Cromer's text, Physics for the life sciences (1974), was required for the course in which the experimental subjects were enrolled, and provided the basic content for the study. The energy chapter in the text (chap. 5) was chosen as the focal point because of the centrality of the concept energy to the development of all physics topics. Lectures based on this text were presented to the experimental group four hours each week throughout one semester of an academic year.

Variables and Related Instrumentation

The major variables of this study are cognitive structure and content structure. The instrumentation necessary for operationalizing these variables will be presented in the following sections.

Cognitive structure. Word association tests operationalized the cognitive structure variable. Seventeen stimulus words were identified for these tests, using as the criterion, their ability to span the range of frequency of occurrence of physics concepts in the energy chapter of Cromer's text. These words were also representative of the author's hypothesized development of energy concepts in cognitive structure in which six clusters form in the following order: kinematics,

dynamics, energy, machines, change of phase, and heat. The seventeen concepts are: distance, time, speed, acceleration, force, mass, weight, gravity, friction, energy, kinetic, potential, mechanical, work, heat, electricity, and atom. The order of these words was varied randomly for each administering of a word association test.

In order to quantify the word association data, the test results were converted into matrices of relatedness coefficients according to the definition of Garskof and Houston (1963). A computer program was prepared to calculate these correlation measures, using the actual associated words as input and providing as output a deck of punched cards containing the relatedness coefficients.

Another computer program, INDSCAL, was used which produces Pearson correlation scores for a matrix of relatedness coefficients with a model matrix. This program, whose method of analysis is canonical decomposition of multiway tables, was designed by Carroll and Chang (1970, 1972). Its procedure is iterative and almost always converges tc absolute minimization of the least squares criterion. The Carroll-Chang method possesses great potential for the study of individual differences (Subkoviak, 1975, p. 410). The need for a model in obtaining the Pearson correlations of the relatedness coefficients leads to the discussion of the next variable, content structure, from which the model is obtained.

Content structure. The model for content structure was obtained from word association data produced by the instructor of the course. The instructor took each word association test administered to the subjects. These were also computer analyzed to produce matrices of relatedness coefficients. These matrix representations of the instructor's cognitive structure served as the model for the content structure of the study. The possibility of establishing models for content structure rests on the assumption that a subject matter structure as represented in the minds of experts such as authors of texts and teachers is fairly stable.

The matrices of relatedness coefficients obtained from the instructor's word association tests were then used as the bases for cluster analyses and multi-dimensional scaling techniques. The OSIRIS computer package (Center for Political Studies, 1973) provides two programs for cluster analysis - HICLSTR and CLUSTER. CLUSTER was used on the model matrices to verify the hypothesized grouping of stimulus concepts. The development of the grouping of the concepts in cognitive structure was then traced by multi-dimensional scaling techniques.

KYST (Kruskal, Young, & Seery, 1973) provided multi-dimensional scaling solutions of the models from the matrices of relatedness coefficients of the instructor. These solutions were then the model or group space with which INDSCAL (Carroll & Chang, 1970, 1972) compared the matrices of relatedness coefficients obtained from the word asso-

ciation tests of individual subjects. The comparisons from INDSCAL are given in the form of Pearson correlations.

Procedures

The data were collected throughout the first semester of an academic year. During the first class period, word association test A was administered to the experimental group. The control group, not being in the class, took the test within several days of the experimental group's schedule. Cromer's text and the lectures presented the key concepts in a detailed fashion according to the hypothesized developmental pattern of the concept - energy. Thus, exposure to the kinematics concepts of distance, time, speed and acceleration preceded instruction on the dynamics or force concepts of mass, weight, gravity and friction. The energy concepts followed the kinematics and force sections, and were defined in terms of them. Machines, change of phase and heat concepts were presented as applications of energy concepts, and therefore were presented subsequent to the energy lectures.

As the sections dealing with the hypothesized stages in the pattern of the development of the energy concept were completed, a word association test to measure cognitive structure was administered. This sequence of instruction periods followed by testing occurred three times during the semester for the experimental group. Again, the word association tests were administered to the control group within several days of the experimental group's schedule. At the end of the semester,

the retention test was again a word association test, taken by all the subjects participating in the study.

To provide a content structure model, the instructor also took each of the five word association tests within several days of administering the tests to the subjects. The instructor did not attempt to constrain responses on any of the five tests to the subject matter currently being covered in the classes. Thus, any one or a combination of all five word association tests might provide the model for the subjects' data.

Design

The word association test was administered in a repeated measures design. All subjects took the word association test at pretesting, and four more times after that. The test was given five times in order to trace the development of physics concepts in the cognitive structure of the subjects after exposure to instructional content. The instructor also took the word association tests to provide the data for the instructional content model.

Results and Discussion

Preliminary Data Reduction

The cognitive structure of each subject at the time of each word association testing was represented by the computer-generated 17 x 17 matrix of relatedness coefficients. The repeated testings at specified intervals provided a means of tracing the development of cognitive structure over a period of time. Content structure was initially provided

by the instructor's five word association tests as depicted in their 17 x 17 matrices of relatedness coefficients.

These matrices were analyzed to determine the single most satisfactory model obtainable from them. The multi-dimensional scaling procedure as operationalized in the computer program, KYST (Kruskal, Young, & Seery, 1973), was used to analyze them structurally. The five dimensional scaling solution produced by the instructor's final word association test had the lowest stress value (.0269), which is analogous to the standard error of estimate in bivariate regression. For this reason and because of the cluster interpretation discussed in the next paragraph, relatedness coefficients of this solution from KYST became the model for future analyses in this study. Table 1 presents the matrix of relatedness coefficients obtained from the instructor's final word association test which was used by KYST to obtain the five-dimensional scaling solution model.

Insert Table 1 about here

To facilitate interpretation of the five dimensions of the established model, the OSIRIS computer program (Center for Political Studies, 1973) for cluster analysis was used. The model relatedness coefficients matrix was the data used for the program. This analysis of the model data grouped the 17 stimulus words into three clusters with four unclustered concepts remaining. The resulting clusters were:

distance, time, speed, acceleration which will be named the kinematics cluster; force, mass, weight, gravity which will be labeled the force cluster; energy, kinetic, potential, mechanical, work which will be the energy cluster. Friction, heat, electricity, and atom were the unclustered concepts. These clusters are consonant with the teaching pattern used to develop the energy theme in which kinematics was presented first; force was introduced next; then, energy. The unclustered items are specific applications of energy which would cluster more appropriately with words extending the concept itself, than with the general energy concepts which the program found grouped together.

Dimensions one and two of the five dimensional structural analysis of the teacher's relatedness coefficients model obtained from KYST are displayed in Figure 1 with the OSIRIS clusters indicated on the graph. By combining these two analyses in this way, one might label the dimensions as cluster separators. Dimension one separates force - kinematics from energy - heat; dimension two separates friction from everything else Further analyses provide similar functions for dimensions three, four and five.

Insert Figure 1 about here

The final step of the data reduction process was to determine the measure for goodness-of-fit of the subjects' relatedness coefficient matrices to the model just established. The five dimensional scaling

solution of the model from KYST was used as the model group space input for INDSCAL (Carroll and Chang, 1970, 1972), the computer program which calculates Pearson correlations of individual's relatedness coefficient matrices with the model matrix. The relatedness coefficient matrix of each subject for each word association test was put into INDSCAL to obtain the correlation coefficient indicating its goodness-of-fit to the model. The correlations were converted to z-scores and increase as the subject approaches the model. Analyses to test the hypothesis will be based on these z-scores. The subject weights on the five dimensions obtained from INDSCAL will abiso be used as a dependent variable providing information about individual differences. The processed data was then used to test the hypothesis of this study which deals with individual differences among subjects.

Individual Differences

The hypothesis of this study states that the cognitive structure of individual college students will approach the structure obtained from instructional content at different rates. The existence of individual differences in the changing of cognitive structure will be demonstrated first. Matrices of relatedness coefficients were formed and the difference between the matrix formed from the word association test given to a learner after a fixed amount of instruction and the one formed from the test given before the instruction was hypothesized to vary from student to student. A regression model was used in which

the dependent variable, change in cognitive structure from session A to session E, was predicted by group (experimental = 1, control = 0). The results of this analysis are presented in Table 2 and indicate that the change in cognitive structure is significantly greater for the experimental group over the control group. Thus, the cognitive structure of those exposed to the content structure changes more than does that of those not exposed to it. The results of this analysis also show much unexplained variance, which means that individual differences are probably operative.

Insert Table 2 about here

The analysis of variance summary of cognitive structure measures presented in Table 3 contains similar information which supports this hypothesis. From that data one can calculate the total units of variance in cognitive structure to be 2.62. Of this total, .9202 units or 35% of the variance is accounted for by the difference in the z-scores of the experimental group from the control group. This again shows that the cognitive structure of individuals exposed to the content structure is different from that of those not exposed to it.

Insert Table 3 about here

One can get more descriptive data in support of this hypothesis by examining individual "person spaces" which can be generated from

the INDSCAL subject weights and the KYST five dimensional scaling solution of the content model. The coordinates of a "person space" for dimensions 1 and 2 (y_{i1}, y_{i2}), $\{i = 1, 2, \ldots 17\}$ for person 1 are a function $(y = \sqrt{w}\, x)$ of the model or group space coordinates (x) and person 1's subject weights (w) (Subkoviak, 1975, p. 407). The graphs in Figures 2 and 3 were constructed in this way to illustrate two persons' cognitive structures, each of whose portrayal occuppies an extreme position on dimension 1 of the model content space. A brief sketch of the progress of these two subjects may provide insight into the information available through this analysis.

Insert Figures 2 and 3 about here

Person C, whose session D space is depicted in Figure 2, was unpredictable in her efforts to master physics. At session A, her subject weight on dimension one was quite low, and her achievement was just below the mean score. At both session B and session C, her weights on dimension one increased progressively, and her achievement scores at these sessions exceeded the mean. However, at session D, her weight on dimension one dropped to the lowest value obtained at any other session by any other subject, and her achievement also dropped to the bottom of the class. At session E, she remained low on dimension one. Achievement also remained low. This sketch demonstrates that for whatever reason, the change in a single subject's cognitive structure is

not even consistently in the same direction. It is possible for clusters which were once differentiated in a person's cognitive structure, to merge again. Future research could profitably investigate the causes of this type of effect, such as declining interest on the part of the subject, lack of stability in long-term memory due to interference or weak initial establishment of the concepts in cognitive structure. Figure 2 illustrates the poorly differentiated clusters.

Person D's session C space is graphed in Figure 3. Person D is a studious person whose consistent efforts are reflected in her cognitive structure changes. Her weight on dimension one was about average at session A. Achievement was slightly above average. At sessions B, C, D, and E her weight on dimension one moved to the highest or second highest value of the class. Her achievement was also consistently high. The session C person space is graphed in Figure 3, as person D's subject weight on dimension one was maximum at this session. In this figure we see the concepts and clusters well differentiated from one another.

The hypothesis has thus been confirmed by the data. The regression analysis resulted in a significant difference between the experimental and control groups in the dependent variable, change in cognitive structure. The large amount of unexplained variance in the prediction of change in cognitive structure also points to the likelihood of operative individual differences. The analysis of variance surfaced

a large difference in the z-scores themselves between individuals in the experimental group which had been exposed to the content model and those in the control group which had not. Finally, it is possible to describe individual person spaces as the subjects are weighted on the five dimensional model space, and to compare the clustering of concepts from individual to individual and from session to session. The instructional process can profitably use the results of an analysis which begins to specify the individual differences in cognitive structure of students, since the object of instruction is to make learning optimal for each individual (Galloway, 1976, p. 383).

Future Studies

The information dealing with individual differences could be used in a number of ways to enhance learner success. Since problem solving achievement is significantly related to cognitive structure (Thro, 1976, pp. 70 - 80), achievement might be heightened by close observation of students' cognitive structures before the administering of tests. If one would monitor the person spaces acquired from the subject weights of INDSCAL on the multi-dimensional scaling solution from KYST, and then provide additional exposure to content material for those whose clusters were not well-differentiated, one could then study dependent variables such as change in achievement, comprehension, and interest, to ascertain the merits of such an application of the techniques of this study.

Conclusion

Providing effective instruction for students is a challenge bounded only by the intelligence and creativity of those who embrace the task. By investigating the relation of cognitive structure to content structure, this study has attempted to lay foundations for future decision making in the instructional process area. Tracing differences in the development of concepts in individuals' cognitive structures is possible and may provide the instructor with a means of increasing students' comprehension and enthusiasm, since achievement has been shown to be related to the differentiation of clustered items in cognitive structure. The value of the cognitive structure variable lies in the additional insight it provides into the state of a learner's progress. Our hope is that this insight will help teachers in their task of guiding students to the full realization of their potential.

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Table 1

Model Relatedness Coefficients Obtained from the Instructor's Final Word Association Test

Distance	Time	Speed	Acceleration	Force	Mass	Weight	Gravity	Friction	Energy	Kinetic	Potential	Mechanical	Work	Heat	Electricity	Atom	
																	Distance
.76																	Time
.67	.66																Speed
.69	.69	.83															Acceleration
.62	.52	.51	.70														Force
.26	.24	.39	.51	.61													Mass
.41	.34	.29	.53	.78	.67												Weight
.45	.37	.30	.55	.70	.53	.80											Gravity
.24	.15	.16	.18	.49	.26	.31	.22										Friction
.42	.38	.60	.45	.40	.52	.29	.26	.36									Energy
.28	.22	.62	.43	.34	.43	.27	.22	.11	.67								Kinetic
.34	.31	.65	.63	.53	.61	.41	.39	.23	.77	.80							Potential
.07	.06	.34	.19	.10	.38	.11	.03	.18	.71	.59	.64						Mechanical
.39	.35	.59	.48	.54	.48	.33	.28	.45	.78	.62	.80	.61					Work
.15	.13	.20	.15	.26	.31	.14	.06	.30	.50	.30	.32	.42	.55				Heat
.28	.27	.34	.37	.28	.34	.30	.29	.16	.50	.42	.44	.28	.41	.18			Electricity
.32	.25	.30	.32	.27	.26	.20	.23	.21	.43	.26	.31	.17	.31	.22	.36		Atom

Table 2

Regression Model Predicting the Dependent Variable, Change in Cognitive Structure, from Groups (Experimental = 1, Control = 0)

Variable	Beta
Groups	.473 **
RSQ	.223 **

**p < .01

Table 3

Analysis of Variance Summary of Experimental and Control Groups' Correlation with the Model. The Variables are: 1) Experimental Group vs. Control Group (A), 2) Subjects (S), and 3) Test Sessions (B).

Source	df	Mean Square	F
Between			
E vs. C (A)	1	.9202	52.5927****
Subjects (S)	28	.017496	
Within			
Sessions (B)	4	.0583	7.3797***
A x B	4	.02525	3.1962**
S x B	112	.0079	

** $p < .01$

*** $p < .001$

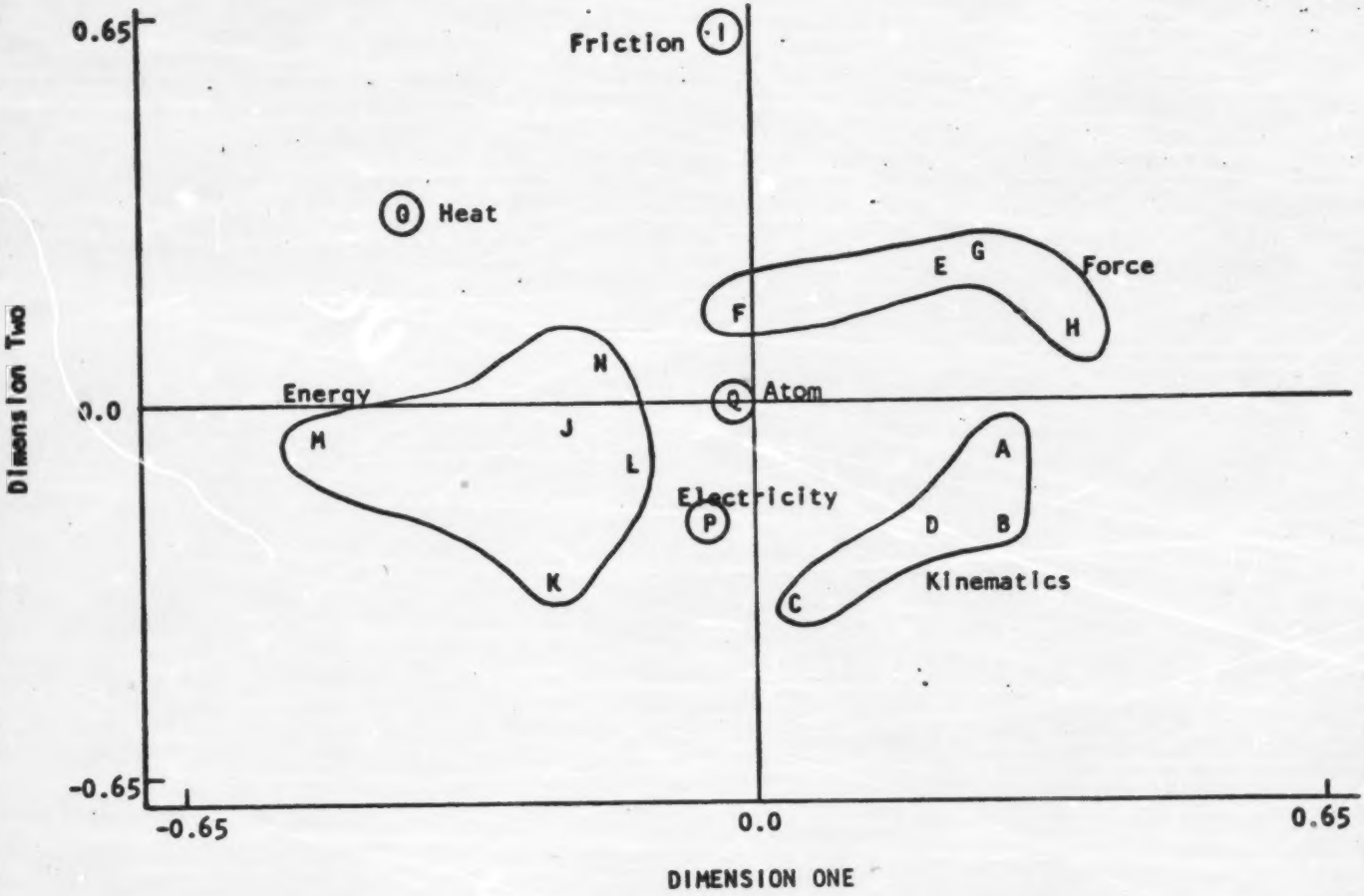
**** $p < .0001$

Figure Captions

Figure 1. Dimensions one and two of the multi-dimensional scaling solution of model relatedness coefficients with clusters indicated.

Figure 2. Person C space at session D for dimensions one and two of the model.

Figure 3. Person D space for session C for dimensions one and two of the model.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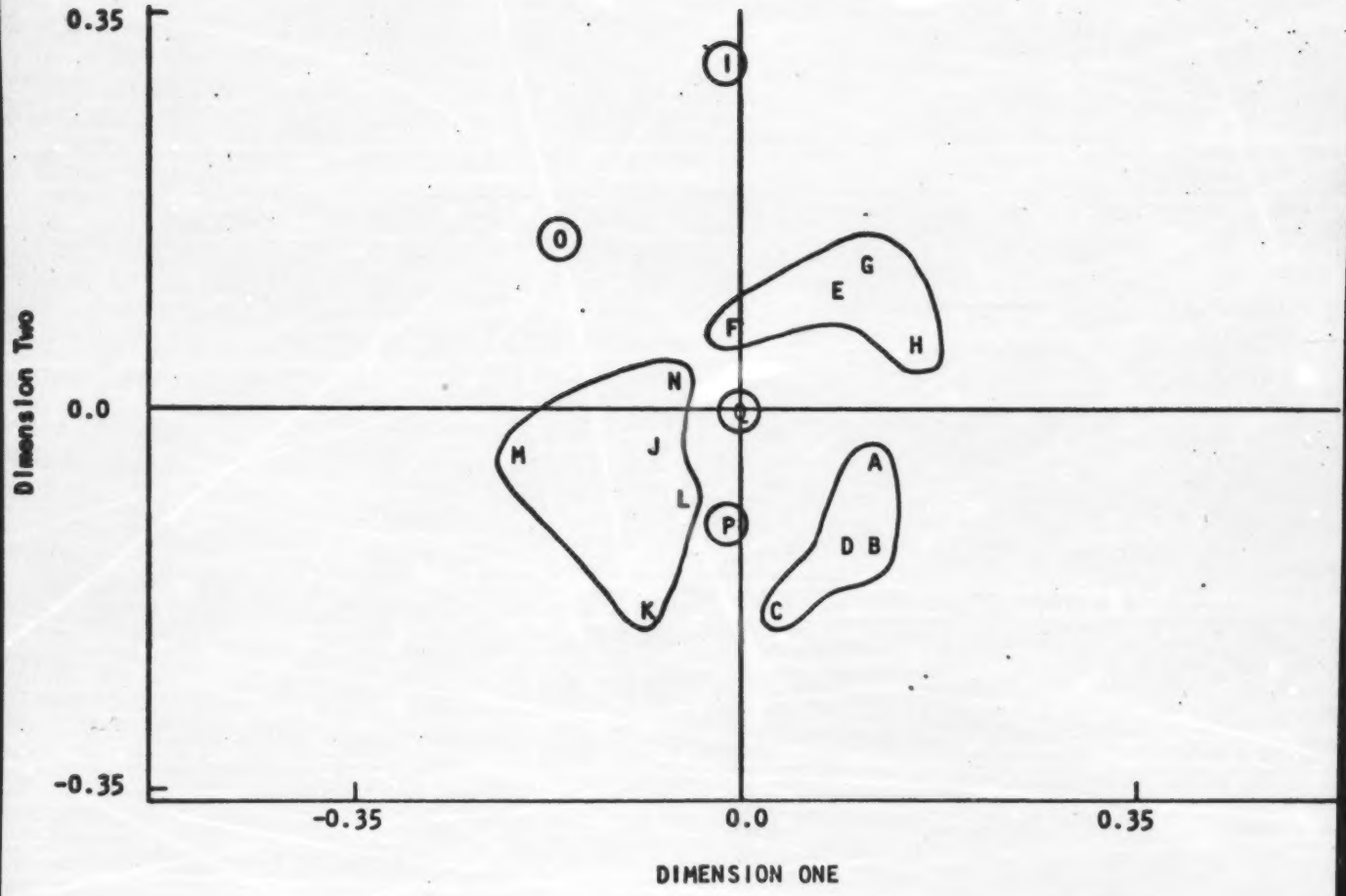
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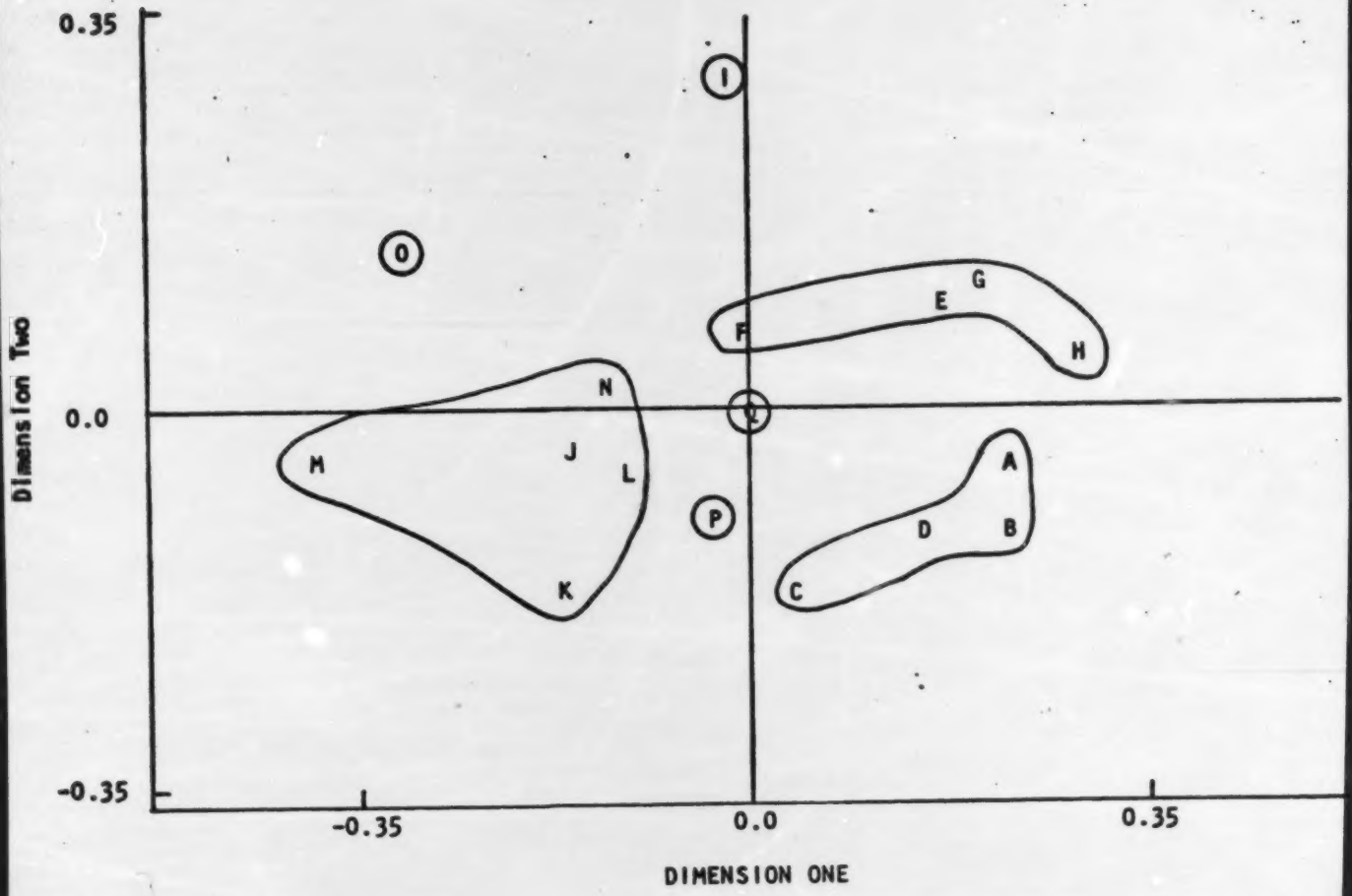
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